

Search for $B^+ \rightarrow \mu^+ \nu_\mu$ with inclusive reconstruction at *BABAR*

The *BABAR* Collaboration

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Abstract

We search for the purely leptonic decay $B^\pm \rightarrow \mu^\pm \nu_\mu$ in the full *BABAR* dataset, having an integrated luminosity of approximately 426 fb^{-1} . We adopt a fully inclusive approach, where the signal candidate is identified by the highest momentum lepton in the event and the companion B is inclusively reconstructed without trying to identify its decay products. We set a preliminary upper limit on the branching fraction of $\mathcal{B}(B^\pm \rightarrow \mu^\pm \nu_\mu) < 1.3 \times 10^{-6}$ at the 90% confidence level, using a Bayesian approach.

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1 INTRODUCTION

In the Standard Model (SM), the purely leptonic B decays $B^+ \rightarrow \ell^+ \nu_\ell$ ($\ell = e, \mu, \tau$) (charge conjugation is implied throughout the paper) proceed through the annihilation of the two quarks in the meson to form a virtual W boson (Fig. 1). The branching ratio can be cleanly calculated in the SM,

$$\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B, \quad (1)$$

where G_F is the Fermi coupling constant, m_ℓ and m_B are the lepton and B meson masses, and τ_B is the B^+ lifetime. The decay rate is sensitive to the Cabibbo Kobayashi Maskawa matrix element V_{ub} and the B decay constant f_B which describes the overlap of the quark wave functions within the meson. Currently, the uncertainty on f_B is one of the main factors limiting the determination of V_{td} from precision $B^0 \bar{B}^0$ mixing measurements. Given a measurement of V_{ub} from semileptonic decays such as $B \rightarrow \pi \ell \nu$, f_B could be extracted from a measurement of the $B^+ \rightarrow \ell^+ \nu_\ell$ branching ratio.

The SM estimate of the branching ratio for $B^+ \rightarrow \tau^+ \nu_\tau$ is $(1.59 \pm 0.40) \times 10^{-4}$ assuming $\tau_B = 1.638 \pm 0.011$ ps, $V_{ub} = (4.39 \pm 0.33) \times 10^{-3}$ [1] determined from inclusive charmless semileptonic B decays and $f_B = 216 \pm 22$ MeV [2] from lattice QCD calculation. Due to helicity suppression, $B^+ \rightarrow \mu^+ \nu_\mu$ and $B^\pm \rightarrow e^\pm \nu_e$ are suppressed by factors of 225 and 10^7 respectively, leading to branching ratios of $\mathcal{B}(B^\pm \rightarrow \mu^\pm \nu_\mu) \simeq 4.7 \times 10^{-7}$ and $\mathcal{B}(B^\pm \rightarrow e^\pm \nu_e) \simeq 1.1 \times 10^{-11}$.

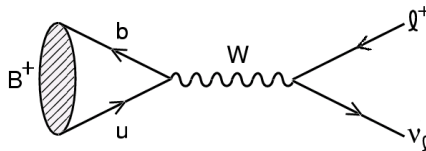


Figure 1: SM annihilation diagram for $B^\pm \rightarrow l^\pm \nu_\mu$.

Purely leptonic B decays are sensitive to physics beyond the SM due to possible insertion of New Physics (NP) heavy states in the annihilation process. Charged Higgs boson effects may greatly enhance or suppress the branching ratio in certain two Higgs doublet models [3]. Similarly, this decay may be enhanced through mediation by leptoquarks in the Pati-Salam model of quark-lepton unification [4].

Moreover, as in annihilation processes the longitudinal component of the vector boson is directly involved, this decay allows a direct test of Yukawa interactions in and beyond the SM. In particular, in a SUSY scenario at large $\tan \beta$ ($O(m_t/m_b) \gg 1$), non-standard effects in helicity-suppressed charged current interactions are potentially observable, being strongly $\tan \beta$ dependent:

$$\mathcal{B}(B^\pm \rightarrow l^\pm \nu_l) \approx \mathcal{B}(B^\pm \rightarrow l^\pm \nu_l)_{\text{SM}} \times \left(1 - \tan^2 \beta m_B^2 / M_H^2\right)^2. \quad (2)$$

Recently, Belle had a first evidence of a purely leptonic B decay. With 414 fb^{-1} , Belle finds [5]

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) = \left(1.79_{-0.49}^{+0.56}(\text{stat})_{-0.51}^{+0.46}(\text{syst})\right) \times 10^{-4}, \quad (3)$$

at 3.5σ significance. The most recent *BABAR* result on this channel uses an integrated luminosity of 346 fb^{-1} , corresponding to 383 million of $B\bar{B}$ pairs, and sets an upper limit (UL) at 90% of confidence level on the branching ratio of $\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau) < 1.7 \times 10^{-4}$ [6] and a central value $\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau) = (1.2 \pm 0.4(\text{stat}) \pm 0.3(\text{bkg}) \pm 0.2(\text{syst})) \times 10^{-4}$ [7].

BABAR has published a result on $\mathcal{B}(B^+ \rightarrow \mu^+\nu_\mu)$ with 81 fb^{-1} and set an UL at 90 % confidence level of $\mathcal{B}(B^+ \rightarrow \mu^+\nu_\mu) < 6.6 \times 10^{-6}$ [8]. The current best published upper limits at 90 % confidence level on $B^+ \rightarrow \mu^+\nu_\mu$ and $B^\pm \rightarrow e^+\nu_e$ are from Belle Collaboration on 235 fb^{-1} [9]

$$\begin{aligned}\mathcal{B}(B^+ \rightarrow \mu^+\nu_\mu) &< 1.7 \times 10^{-6}, \\ \mathcal{B}(B^+ \rightarrow e^+\nu_e) &< 9.8 \times 10^{-7}.\end{aligned}\tag{4}$$

2 THE *BABAR* DETECTOR AND DATASET

This analysis is based on the data collected with the *BABAR* detector [10] at the PEP-II storage ring. The sample corresponds to an integrated luminosity of 426 fb^{-1} at the $\Upsilon(4S)$ resonance, consisting of about 447 millions of $B\bar{B}$ pairs, and 44 fb^{-1} accumulated at a center-of-mass (CM) energy about 40 MeV below the $\Upsilon(4S)$ resonance. Off-resonance data are used as cross-checks for continuum $q\bar{q}$ ($q = u, d, s$, and \bar{c}) and $\tau^+\tau^-$ on-resonance events. In particular, given the variation of muon identification in time due to detector differences and changes, we considered the total dataset divided into data-taking periods (runs).

Charged track reconstruction is provided by a Silicon Vertex Tracker (SVT) and a Drift Chamber (DCH) operating in a 1.5-T magnetic field. Particle identification is based on the energy loss dE/dx in the tracking system and the Cherenkov angle in an internally reflecting ring-imaging Cherenkov detector. Photon detection is provided by a CsI(Tl) Electromagnetic Calorimeter (EMC). Muons and neutral hadrons are identified by Resistive Plate Chambers and Limited Streamer Tubes in the Instrumented Flux Return (IFR) detector.

A GEANT4-based [11] Monte Carlo (MC) simulation is used to model the detector response and test the analysis technique. A sample of about 28 million simulated B^+B^- events where B^+ decays to $\mu^+\nu_\mu$ and the B^- decays generically is studied to evaluate the efficiency for the signal. Background sources considered include $e^+e^- \rightarrow B\bar{B}$, $e^+e^- \rightarrow q\bar{q}$ ($q = u, d, s$, and \bar{c}), and $e^+e^- \rightarrow \tau^+\tau^-$ in quantities comparable to three times ($B\bar{B}$), twice ($c\bar{c}$) and once ($uds, \tau^+\tau^-$) the actual dataset luminosity.

3 ANALYSIS METHOD

$B^+ \rightarrow \mu^+\nu_\mu$ is a two-body decay so the muon must be mono-energetic in the B rest frame. The momentum p^* of the muon in the B rest frame is given by

$$p^* = \frac{m_B^2 - m_\mu^2}{2m_B} \approx \frac{m_B}{2} \approx 2.46\text{ GeV}.\tag{5}$$

where m_B is the B mass and m_μ is the muon mass. At *BABAR* the CM frame is a good approximation to the B rest frame, so we initially select well-identified muon candidates with momentum p_{CM} between 2.4 and 3.2 GeV/ c in the CM frame. Since the neutrino produced in the signal decay is not detected, any other charged tracks or neutral deposits in a signal event must have been produced by the decay of the companion (tag) B . Therefore, the tag B can be reconstructed from the remaining

visible energy in the event. Signal decays can then be selected using the kinematic variables ΔE and energy-substituted mass, m_{ES} , defined by

$$\Delta E = E_B - E_{\text{beam}}, \quad (6)$$

and

$$m_{ES} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_B|^2}, \quad (7)$$

where \vec{p}_B and E_B are the momentum and energy of the reconstructed tag B candidate in the CM frame and E_{beam} is the beam energy in the CM frame. We include all neutral calorimeter clusters with cluster energy greater than 30 MeV. Particle identification is applied to the charged tracks to identify electrons, muons, kaons and protons in order to apply the most likely mass hypothesis to each track and thus improve the ΔE and m_{ES} resolution. Events with additional identified leptons are discarded to discriminate against events containing additional neutrinos. For signal events in which all decay products of the other B are reconstructed, we expect the ΔE distribution to peak near zero and m_{ES} to peak near m_B . In reality, due to the inclusive nature of our analysis, we often fail to reconstruct all the decay products so that the ΔE distribution develops a negative tail while the m_{ES} distribution exhibits a tail below the B mass. For uds and $c\bar{c}$ backgrounds, ΔE is shifted significantly greater than zero since we attribute too much energy to the opposite hemisphere decay. ΔE is negative for $\tau^+\tau^-$ decays due to missing neutrinos. Figure 2 shows the distributions of ΔE and m_{ES} for the on-peak data, background MC and signal MC after muon candidate selection.

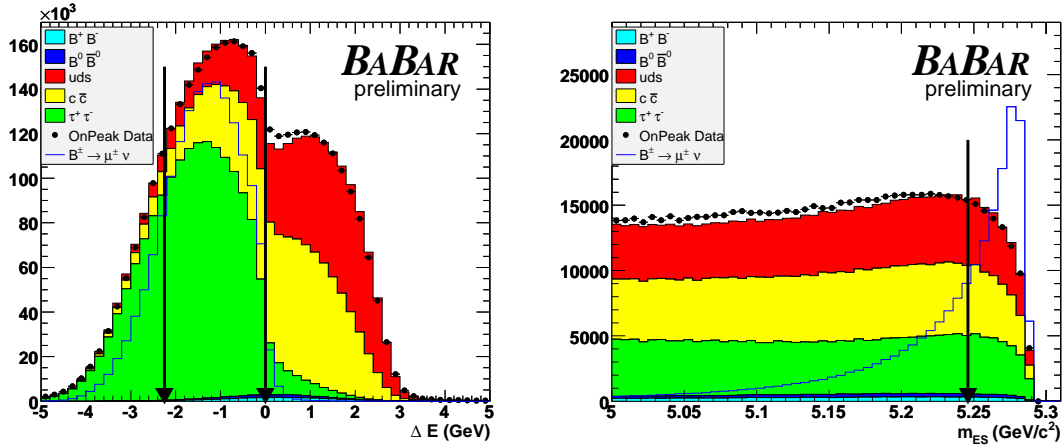


Figure 2: Distribution of ΔE and m_{ES} after the muon selection: signal in blue histogram, data in black dots and background events are stacked on top of each other: uds in red, $c\bar{c}$ in yellow, $\tau^+\tau^-$ in green, $B^0\bar{B}^0$ in dark blue and B^+B^- in light blue. The arrows indicate the requirements set on these variables.

In order to obtain data/MC agreement, we extract the uds , $c\bar{c}$ and $\tau^+\tau^-$ MC normalization coefficients from a fit to the ΔE data distribution, keeping the $b\bar{b}$ component fixed. The requirements on tag B kinematical variables is optimized with the figure of merit $\epsilon_{\text{sig}}/\sqrt{N_{\text{bkg}}}$ where ϵ_{sig} is the signal efficiency and N_{bkg} the number of background events. We require the tag B ΔE and m_{ES} to be within $-2.25 < \Delta E < 0$ GeV and $m_{ES} > 5.246$ GeV/ c^2 .

Once the tag B is reconstructed, we refine the estimate of the muon momentum in the B rest frame (p^*). We use the momentum direction of the tag B and assume a total momentum of 320 MeV/ c in the CM frame (from the decay of the $\Upsilon(4S) \rightarrow B\bar{B}$) to boost the muon candidate into the reconstructed B rest frame.

Backgrounds may arise from any process producing charged tracks in the momentum range of the signal, particularly if the charged tracks are muons. The two most significant backgrounds are B semileptonic decays involving $b \rightarrow u\mu\nu_\mu$ transitions where the endpoint of the muon spectrum approaches that of the signal, and non-resonant $q\bar{q}$ (continuum) events where a charged pion is mistakenly identified as a muon. In the continuum events, there must also be significant missing energy due to detector acceptance, neutral hadrons, or additional neutrinos that mimic the signature of the expected neutrino.

Continuum backgrounds are suppressed using event shape variables. The light-quark events tend to produce a jet-like event topology as opposed to $B\bar{B}$ events which tend to be more isotropically distributed in space. Several topological variables have been considered and five have been found to be the most discriminating, using an appropriate cocktail of different data-taking periods. These variables are combined in a Fisher discriminant [12]: the normalized second Fox-Wolfram moment R_2 [13], calculated using all charged tracks and neutral clusters in the event; the ratio of the second and zeroth Legendre Polynomials L_2/L_0 , where all tag B daughters momenta in the CM frame are included and the angle is measured with respect to the lepton candidate momentum; the cosine of the angle of the expected signal neutrino in the lab frame (as determined from the lepton candidate); the lepton transverse momentum in $\Upsilon(4S)$ frame; the sphericity of the event. The Fisher coefficients are optimized run-by-run. A cut is applied on the Fisher discriminant and is thus optimized for each run separately in order to have better performance. The efficiency of this cut is in the range 16% to 32% for signal events, 5% to 16% for $b\bar{b}$ events and less than 0.5% for continuum events.

The two-body kinematics of this decay is now exploited by combining p^* and p_{CM} in a second Fisher discriminant in order to discriminate against the remaining semileptonic $b\bar{b}$ background events. Signal and background yields are obtained from a Maximum Likelihood Fit using the Fisher output p_{FIT} . We parameterize signal MC with the sum of two Gaussians. As $b\bar{b}$ events and continuum $q\bar{q}$ and $\tau^+\tau^-$ events are two background samples with different p_{FIT} Probability Density Functions (PDFs), we parameterize them separately and construct a summed background PDF with relative normalizations fixed from simulated events. Both of them are parameterized with a Gaussian function with a different sigma for value above and below the peak (bifurcated Gaussians). Table 1 shows the fixed parameterization of signal and backgrounds PDFs, with purely statistical uncertainties arising from the size of the simulated datasets used to obtain the parameterizations. The p_{FIT} distributions for simulated signal and background events are shown in Figure 3. Only the signal yield and the yield of the sum of all backgrounds are free parameters in the fit.

4 SYSTEMATIC STUDIES

To set an upper limit on the $B^+ \rightarrow \mu^+\nu_\mu$ branching fraction we evaluate systematic uncertainties in the number of B^\pm in the sample, the signal efficiency and the signal yield.

- The number of B^\pm mesons in the on-peak data sample is estimated to be 447×10^6 with an uncertainty of 1.1% estimated studying $\mu\mu$ pairs events [14].

Table 1: p_{FIT} distribution parameterization for signal MC (left), $b\bar{b}$ (center) and $uds + c\bar{c} + \tau^+\tau^-$ (right). The two summed Gaussians have parameters $(\mu_{\text{core}}, \sigma_{\text{core}})$ and $(\mu_{\text{tail}}, \sigma_{\text{tail}})$ respectively and f_{core} is the relative fraction of the core Gaussian. The bifurcated Gaussian has μ_{core} as mean and σ_L and σ_R as left and right σ respectively.

Parameter	Signal MC	$b\bar{b}$	$uds + c\bar{c} + \tau^+\tau^-$
μ_{core}	5.32 ± 0.03	-2.2 ± 0.3	0.5 ± 1.1
$\sigma_{\text{core(L)}}$	2.43 ± 0.04	0.7 ± 0.2	1.6 ± 0.7
μ_{tail}	4.91 ± 0.03	-	-
$\sigma_{\text{tail(R)}}$	1.39 ± 0.04	3.6 ± 0.3	6.8 ± 0.9
f_{core}	0.54 ± 0.03	-	-

- The uncertainty in the signal efficiency includes the muon candidate selection (particle identification, tracking efficiency and Fisher requirement) as well as the reconstruction efficiency of the tag B . The muon identification efficiency systematic is evaluated using control samples derived from the *BABAR* data, which are weighted to reproduce the kinematic distribution of the muon signal candidate. Comparing the cumulative signal efficiency obtained with and without this weight, a total discrepancy of 2.9% is found and this value is taken as the muon ID systematic uncertainty.

Charge conservation is imposed on τ decays, which must proceed via an odd number of tracks and thus the number of events with a missing track can be used to evaluate the uncertainty associated with the tracking efficiency and the relative correction factor. The systematic uncertainty per track and the correction factor are taken in quadrature to give the total tracking efficiency uncertainty of 0.4% per track.

In order to evaluate the systematic uncertainty associated with the requirements on the Fisher discriminants, we take the ratio between data and simulated events Fisher discriminant distributions in the ΔE and m_{ES} sidebands $\Delta E > 0$ GeV and $5.2 \text{ GeV}/c^2 < m_{ES} < 5.246 \text{ GeV}/c^2$ for each different data-taking period. We fit the data/MC ratio for each run with a linear function. The mean weighted by the errors of slopes and intercepts returns a linear function consistent with a data/MC unitary ratio in the full Fisher range. We take the uncertainty of 1.5% on the averaged intercept as the systematic error on the Fisher discriminant cut.

The tag B reconstruction has been studied with a control sample of $B^+ \rightarrow D^{(*)0}\pi^+$ events, where the D is reconstructed into $\bar{D}^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$ and the D^* into $D^{*0} \rightarrow D^0\gamma$ or $D^{*0} \rightarrow D^0\pi^0$. This is also a two-body decay so it is topologically very similar to our signal. Once reconstructed, the pion can be treated as if it were the signal muon and the $D^{(*)0}$ decay products are ignored to simulate the neutrino. The tag B is then reconstructed in the control sample as it would be for signal. We compare the efficiencies for our tag B selection cuts in the $B^+ \rightarrow D^{(*)0}\pi^+$ data and MC to quantify any data/MC disagreements that may affect the signal efficiency. We find a data/MC discrepancy on $B^+ \rightarrow D^{(*)0}\pi^+$ control sample of 2.7% and assign this as the signal efficiency uncertainty arising from the tag B selection. A summary of the systematic uncertainties in the signal efficiency is given in Table 2. The final signal efficiency is thus 4.64 ± 0.19 %.

- The fit parameters are extracted from MC and are kept fixed in the final fit to extract the

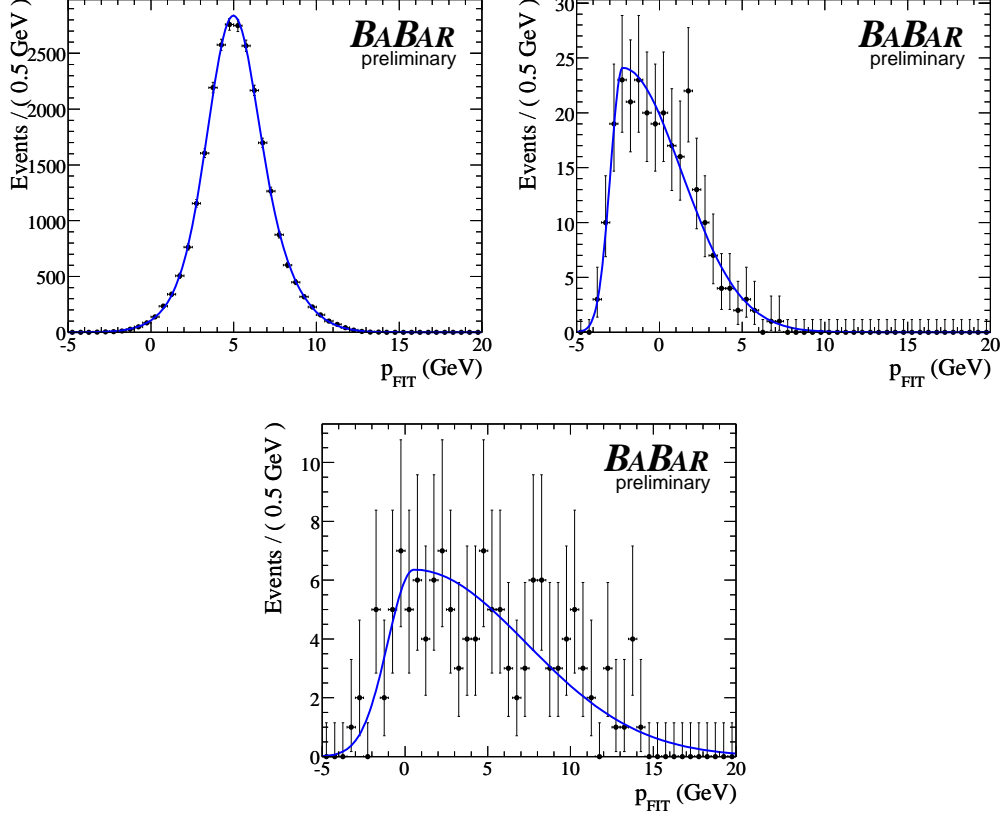


Figure 3: Distribution of p_{FIT} with the fit superimposed: signal (top left), $b\bar{b}$ (top right) and $c\bar{c} + uds + \tau^+\tau^-$ (bottom).

Table 2: Contributions to the systematic uncertainty on the signal efficiency.

Source	Relative Error
muon identification	2.9%
tracking efficiency	0.4%
tag B reconstruction	2.7%
Fisher selection	1.5%
Total	4.2%

yields. These parameters are affected by an uncertainty due to the MC statistics, which is considered as a source of systematic uncertainty. In order to evaluate it, the final fit has been repeated 500 times for each background and signal PDF parameter. We randomly generate the PDF parameters assuming Gaussian errors and taking into account all the correlations between them. We perform a Gaussian fit to the distribution of the number of signal events for each parameter, take the fitted sigma as the systematic uncertainty and sum in quadrature. The total systematic uncertainty in the signal yield from all signal and background PDFs

parameterization is 13 events.

We take into account possible discrepancies in the shape of the p_{FIT} background distribution in data and simulated events using again the simulated events over data ratio in the ΔE and m_{ES} sidebands $\Delta E > 0$ GeV and $5.2 < m_{ES} < 5.246$ GeV/c². Given the low statistics available for values of p_{FIT} above 5, we parameterize this ratio with a parabolic function in the region (-5;5) and take the constant value of the ratio in the region (5;20). The ratio with the parabolic fit superimposed is shown in Figure 4. We repeat the final fit to the data 500 times for each parabola parameter and the value of the constant. We generate each parameter according to a Gaussian distribution centered at its mean value and having a sigma equal to its error, taking into account all correlations between different parameters. We weight the dataset by the generated ratio and repeat the fit. A Gaussian fit to the distribution of number of fitted signal events for each parameter is performed and the sigma of the the Gaussian fit is taken as systematic uncertainty and summed in quarature. The total systematic uncertainty from this procedure is 7 events. A summary of all systematic uncertainties in the fitted signal yield is provided in Table 3.

The total systematic uncertainty is 1.1% on the number of B^+B^- pairs, 4.2 % on signal efficiency and 15 events on the signal yield.

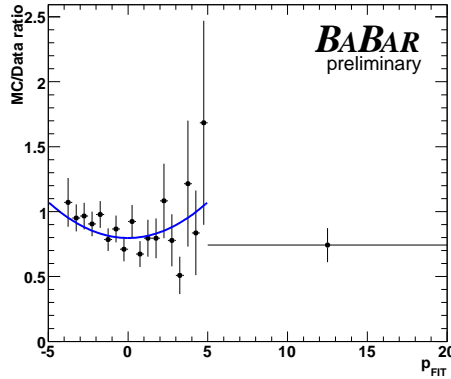


Figure 4: MC/Data ratio of p_{FIT} distribution on ΔE and m_{ES} sideband ($\Delta E > 0$ GeV and 5.2 GeV/c² $< m_{ES} < 5.246$ GeV/c²).

Table 3: Contributions to the systematic uncertainty on the signal yield.

Source	Total Error
PDF parameters	13
Data/MC agreement	7
Total	15

5 RESULTS

From the data we extract -12 ± 15 signal events and 600 ± 29 background events. We expect 10 events from MC assuming a SM branching fraction $\mathcal{B}(B^\pm \rightarrow \mu^\pm \nu_\mu) = 4.7 \times 10^{-7}$. The signal yield extracted corresponds to a central value $\mathcal{B}(B^\pm \rightarrow \mu^\pm \nu_\mu) = (-5.7 \pm 7.1(\text{stat}) \pm 6.8(\text{syst})) \times 10^{-7}$. Figure 5 shows the data points with the final fit superimposed.

Given the number of fitted signal events, the signal efficiency and including all systematic uncertainties, we find the Bayesian UL assuming a flat prior for the branching fraction up to a maximum of $\mathcal{B}(B^\pm \rightarrow \mu^\pm \nu_\mu) = 3 \times 10^{-6}$ to be

$$\mathcal{B}(B^+ \rightarrow \mu^+ \nu_\mu) < 1.3 \times 10^{-6}$$

at the 90% confidence level. The 95% Bayesian UL is $\mathcal{B}(B^+ \rightarrow \mu^+ \nu_\mu) < 1.6 \times 10^{-6}$. These results are more restrictive than previous measurements from *BABAR* [8] and Belle [9].

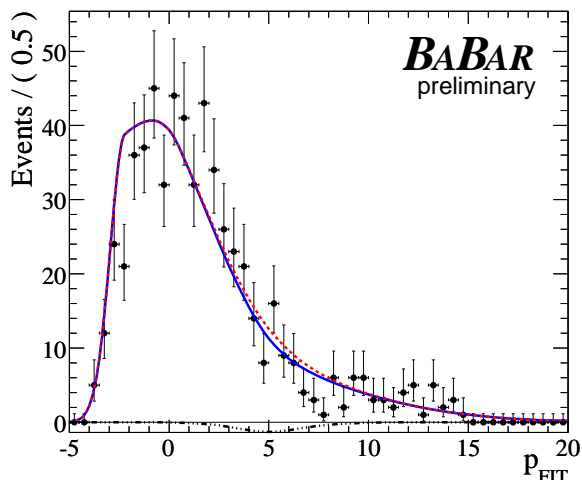


Figure 5: Final fit to the data p_{FIT} distribution: full blue line is the total distribution, dashed red line is background distribution, dashed-dotted black line is signal distribution.

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References

- [1] E. Barberio *et al.* [Heavy Flavor Averaging Group (HFAG)].
- [2] A. Gray *et al.* [HPQCD Collaboration], Phys. Rev. Lett. **95** (2005) 212001.
- [3] W. S. Hou, Phys. Rev. D **48** (1993) 2342.
- [4] G. Valencia and S. Willenbrock, Phys. Rev. D **50** (1994) 6843.
- [5] K. Ikado *et al.*, Phys. Rev. Lett. **97** (2006) 251802.
- [6] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **76** (2007) 052002.
- [7] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **77** (2008) 011107.
- [8] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **92** (2004) 221803.
- [9] N. Satoyama *et al.* [Belle Collaboration], Phys. Lett. B **647** (2007) 67.
- [10] B. Aubert *et al.* [BABAR Collaboration], *Nucl. Instrum. Methods A* **479**, 1-116 (2002).
- [11] S. Agostinelli *et al.* [GEANT4 Collaboration], Nucl. Instrum. Meth. A **506** (2003) 250.
- [12] R. A. Fisher, Ann. Eugenics **7** (1936) 179; G. Cowan, *Statistical Data Analysis*, (Oxford University Press, 1998), p. 51.
- [13] G. C. Fox and S. Wolfram, Phys. Rev. Lett. **41** (1978) 1581.
- [14] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. D **67** (2003) 032002.